

# Next-generation nuclear DIS: spectator tagging with light ions at an EIC

Wim Cosyn

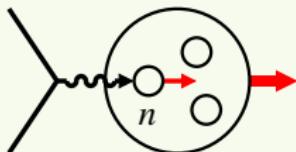
Ghent University, Belgium

Poetic 7/CTEQ meeting  
Temple University

in collaboration with  
Ch. Weiss (JLab) & M. Sargsian (FIU)  
JLab LRD project on spectator tagging

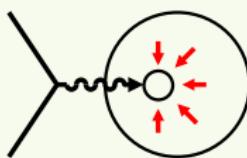


# Light ions: physics objectives



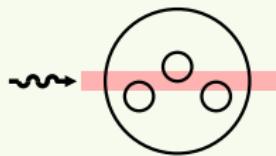
## ■ Neutron structure

- ▶ flavor decomposition of quark PDFs/GPDs/TMDs
- ▶ flavor structure of the nucleon sea
- ▶ singlet vs non-singlet QCD evolution, leading/higher-twist effects



## ■ Bound nucleons in QCD

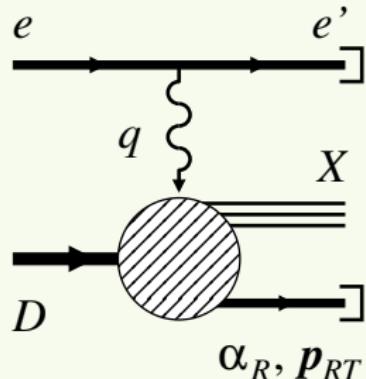
- ▶ medium modification of quark/gluon structure
- ▶ QCD origin of short-range nuclear force



## ■ Coherence and saturation

- ▶ interaction of high-energy probe with coherent quark-gluon fields

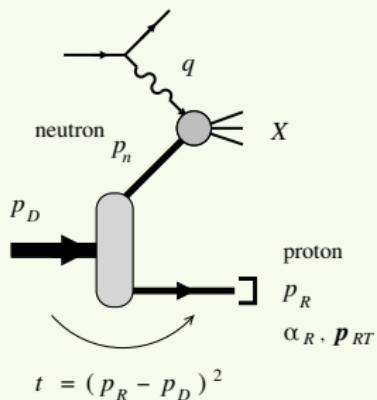
# Tagged spectator DIS process with deuteron



- DIS off a nuclear target with a slow (relative to nucleus c.m.) nucleon detected in the final state
- Control nuclear configuration
- Advantages for the deuteron
  - ▶ simple  $NN$  system, non-nucleonic ( $\Delta\Delta$ ) dof suppressed
  - ▶ active nucleon identified
  - ▶ recoil momentum selects nuclear configuration (medium modifications)
  - ▶ limited possibilities for nuclear FSI, calculable
- Wealth of possibilities to study (nuclear) QCD dynamics
- Will be possible in a wide kinematic range @ EIC (**polarized** for JLEIC)
- suited for colliders: no target material, forward detection, transverse pol.  
fixed target CLAS BONuS limited to recoil momenta  $\sim 70$  MeV

# Pole extrapolation for on-shell nucleon structure

- Allows to extract free neutron structure in a **model independent** way
  - ▶ Recoil momentum  $p_R$  controls off-shellness of neutron  $t - m_N^2$
  - ▶ Free neutron at pole  $t - m_N^2 \rightarrow 0$ : "on-shell extrapolation"
  - ▶ Small deuteron binding energy results in small extrapolation length
  - ▶ Eliminates nuclear binding and FSI effects  
[Sargsian, Strikman PLB '05]
  - ▶ Pole is present in non-rel deuteron wf  
[AV18, Bonn, etc.]
- D-wave suppressed at on-shell point  $\rightarrow$  neutron  $\sim 100\%$  polarized
- Precise measurements of neutron structure at an EIC



# What is needed?

- General expression of SIDIS for a polarized spin 1 target
  - ▶ Tagged spectator DIS is SIDIS in the target fragmentation region

$$\vec{e} + \vec{T} \rightarrow e' + X + h$$

- Dynamical model to express structure functions of the reaction
  - ▶ First step: impulse approximation (IA) model
- Light-front structure of the deuteron
  - ▶ Natural for high-energy reactions as **off-shellness of nucleons** in LF quantization remains **finite**

# Polarized spin 1 particle

- Spin state described by a 3\*3 density matrix in a basis of spin 1 states polarized along the collinear virtual photon-target axis

$$W_D^{\mu\nu} = \text{Tr}[\rho_{\lambda\lambda'} W^{\mu\nu}(\lambda'\lambda)]$$

- Characterized by **3 vector** and **5 tensor** parameters

$$S^\mu = \langle \hat{W}^\mu \rangle, \quad T^{\mu\nu} = \frac{1}{2} \sqrt{\frac{2}{3}} \langle \hat{W}^\mu \hat{W}^\nu + \hat{W}^\nu \hat{W}^\mu + \frac{4}{3} \left( g^{\mu\nu} - \frac{\hat{P}^\mu \hat{P}^\nu}{M^2} \right) \rangle$$

- Split in longitudinal and transverse components

$$\rho_{\lambda\lambda'} = \frac{1}{3} \begin{bmatrix} 1 + \frac{3}{2} S_L + \sqrt{\frac{3}{2}} T_{LL} & \frac{3}{2\sqrt{2}} S_T e^{-i(\phi_h - \phi_S)} & \sqrt{\frac{3}{2}} T_{TT} e^{-i(2\phi_h - 2\phi_T)} \\ -\sqrt{3} T_{LT} e^{-i(\phi_h - \phi_T)} & 1 - \sqrt{6} T_{LL} & \frac{3}{2\sqrt{2}} S_T e^{-i(\phi_h - \phi_S)} \\ -\sqrt{3} T_{LT} e^{i(\phi_h - \phi_T)} & \frac{3}{2\sqrt{2}} S_T e^{i(\phi_h - \phi_S)} & 1 - \frac{3}{2} S_L + \sqrt{\frac{3}{2}} T_{LL} \end{bmatrix}.$$

# Spin 1 SIDIS: General structure of cross section

- To obtain structure functions, enumerate all possible tensor structures that obey hermiticity and transversality condition ( $qW_D = W_D q = 0$ )
- Cross section has **41 structure functions**,

$$\frac{d\sigma}{dx dQ^2 d\phi_{l'}} = \frac{y^2 \alpha^2}{Q^4(1-\epsilon)} (F_U + F_S + F_T) d\Gamma_{P_h},$$

- ▶ U + S part identical to spin 1/2 case [Bacchetta et al. JHEP ('07)]

$$F_U = F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \epsilon \cos 2\phi_h F_{UU}^{\cos 2\phi_h} + h \sqrt{2\epsilon(1-\epsilon)} \sin \phi_h F_{LU}^{\sin \phi_h}$$

$$\begin{aligned} F_S = & S_L \left[ \sqrt{2\epsilon(1+\epsilon)} \sin \phi_h F_{US_L}^{\sin \phi_h} + \epsilon \sin 2\phi_h F_{US_L}^{\sin 2\phi_h} \right] \\ & + S_L h \left[ \sqrt{1-\epsilon^2} F_{LS_L} + \sqrt{2\epsilon(1-\epsilon)} \cos \phi_h F_{LS_L}^{\cos \phi_h} \right] \\ & + S_{\perp} \left[ \sin(\phi_h - \phi_S) \left( F_{US_{T,T}}^{\sin(\phi_h - \phi_S)} + \epsilon F_{US_{T,L}}^{\sin(\phi_h - \phi_S)} \right) + \epsilon \sin(\phi_h + \phi_S) F_{US_T}^{\sin(\phi_h + \phi_S)} \right. \\ & \left. + \epsilon \sin(3\phi_h - \phi_S) F_{US_T}^{\sin(3\phi_h - \phi_S)} + \sqrt{2\epsilon(1+\epsilon)} \left( \sin \phi_S F_{US_T}^{\sin \phi_S} + \sin(2\phi_h - \phi_S) F_{US_T}^{\sin(2\phi_h - \phi_S)} \right) \right] \\ & + S_{\perp} h \left[ \sqrt{1-\epsilon^2} \cos(\phi_h - \phi_S) F_{LS_T}^{\cos(\phi_h - \phi_S)} + \right. \\ & \left. \sqrt{2\epsilon(1-\epsilon)} \left( \cos \phi_S F_{LS_T}^{\cos \phi_S} + \cos(2\phi_h - \phi_S) F_{LS_T}^{\cos(2\phi_h - \phi_S)} \right) \right], \end{aligned}$$

# Spin 1 SIDIS: General structure of cross section

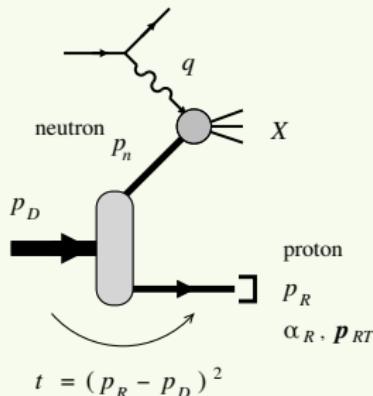
- To obtain structure functions, enumerate all possible tensor structures that obey hermiticity and transversality condition ( $\mathbf{q}W_D = W_D\mathbf{q} = 0$ )
- Cross section has **41 structure functions**,

$$\frac{d\sigma}{dx dQ^2 d\phi_{l'}} = \frac{y^2 \alpha^2}{Q^4(1-\epsilon)} (F_U + F_S + F_T) d\Gamma_{P_h},$$

- ▶ **23 SF** unique to the spin 1 case (tensor pol.), 4 survive in inclusive ( $b_{1-4}$ ) [Hoodbhoy, Jaffe, Manohar PLB'88]

$$\begin{aligned} F_T = & \textcolor{teal}{T}_{LL} \left[ F_{UT_{LL,T}} + \epsilon F_{UT_{LL,L}} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_h F_{UT_{LL}}^{\cos \phi_h} + \epsilon \cos 2\phi_h F_{UT_{LL}}^{\cos 2\phi_h} \right] \\ & + \textcolor{teal}{T}_{LL} \textcolor{brown}{h} \sqrt{2\epsilon(1-\epsilon)} \sin \phi_h F_{LT_{LL}}^{\sin \phi_h} \\ & + \textcolor{teal}{T}_{L\perp} [\dots] + \textcolor{teal}{T}_{L\perp} \textcolor{brown}{h} [\dots] \\ & + \textcolor{teal}{T}_{\perp\perp} \left[ \cos(2\phi_h - 2\phi_{T_\perp}) \left( F_{UT_{TT,T}}^{\cos(2\phi_h - 2\phi_{T_\perp})} + \epsilon F_{UT_{TT,L}}^{\cos(2\phi_h - 2\phi_{T_\perp})} \right) \right. \\ & + \epsilon \cos 2\phi_{T_\perp} F_{UT_{TT}}^{\cos 2\phi_{T_\perp}} + \epsilon \cos(4\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(4\phi_h - 2\phi_{T_\perp})} \\ & \left. + \sqrt{2\epsilon(1+\epsilon)} \left( \cos(\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(\phi_h - 2\phi_{T_\perp})} + \cos(3\phi_h - 2\phi_{T_\perp}) F_{UT_{TT}}^{\cos(3\phi_h - 2\phi_{T_\perp})} \right) \right] \\ & + \textcolor{teal}{T}_{\perp\perp} \textcolor{brown}{h} [\dots] \end{aligned}$$

# Tagged DIS with deuteron: model for the IA



- Hadronic tensor can be written as a product of nucleon hadronic tensor with deuteron light-front densities

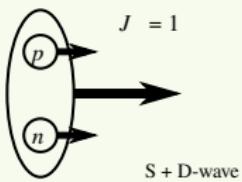
$$W_D^{\mu\nu}(\lambda', \lambda) = 4(2\pi)^3 \frac{\alpha_R}{2 - \alpha_R} \sum_{i=U,z,x,y} W_{N,i}^{\mu\nu} \rho_D^i(\lambda', \lambda),$$

All SF can be written as

$$F_{ij}^k = \{\text{kin. factors}\} \times \{F_{1,2}(\tilde{x}, Q^2) \text{ or } g_{1,2}(\tilde{x}, Q^2)\} \times \{\text{bilinear forms in light-front deuteron radial wave function } S(k), D(k)\}$$

- In the IA the following structure functions are **zero** → sensitive to FSI
  - ▶ beam spin asymmetry  $[F_{LU}^{\sin \phi_h}]$
  - ▶ target vector polarized single-spin asymmetry [8 SFs]
  - ▶ target tensor polarized double-spin asymmetry [7 SFs]

# Deuteron light-front wave function

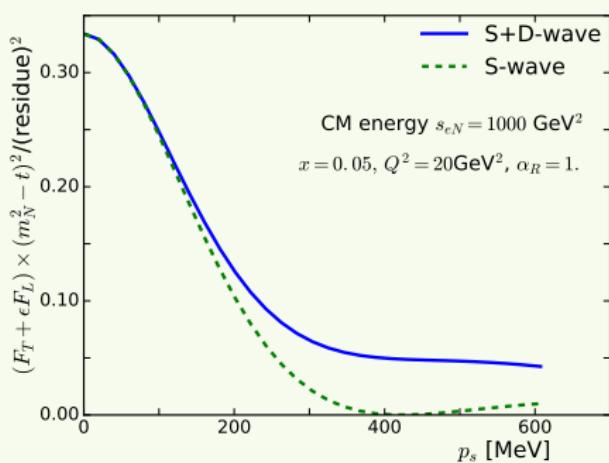


- Up to momenta of a few 100 MeV dominated by  $NN$  component
- Can be evaluated in LFQM [Coester,Keister,Polyzou et al.] or covariant Feynman diagrammatic way [Frankfurt,Sargsian,Strikman]
- One obtains a Schrödinger (non-rel) like eq. for the wave function components, **rotational invariance recovered**
- Light-front WF obeys **baryon and momentum sum rule**

$$\Psi_{\lambda}^D(\mathbf{k}_f, \lambda_1, \lambda_2) = \sqrt{E_{kf}} \sum_{\lambda'_1 \lambda'_2} \mathcal{D}_{\lambda'_1 \lambda'_2}^{\frac{1}{2}} [\mathcal{R}_{fc}(k_{1_f}^{\mu} / m_N)] \mathcal{D}_{\lambda'_2 \lambda'_2}^{\frac{1}{2}} [\mathcal{R}_{fc}(k_{2_f}^{\mu} / m_N)] \Phi_{\lambda}^D(\mathbf{k}_f, \lambda'_1, \lambda'_2)$$

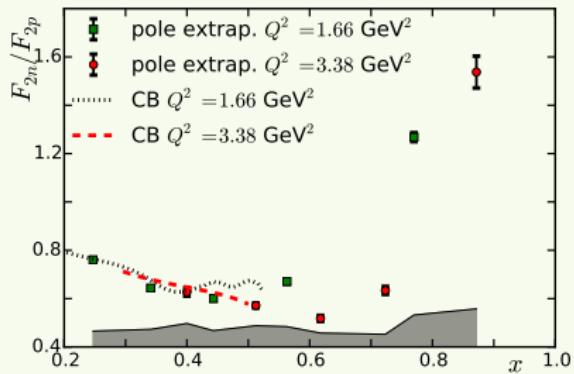
- **Differences** with non-rel wave function:
  - ▶ appearance of the **Melosh rotations** to account for light-front quantized nucleon states
  - ▶  $\mathbf{k}_f$  is the relative 3-momentum of the nucleons in the light-front boosted rest frame of the free 2-nucleon state (so not a "true" kinematical variable)

# Unpolarized structure function $F_T + \epsilon F_L$



- Extrapolation for  $(m_N^2 - t) \rightarrow 0$  corresponds to on-shell neutron  $F_{2N}(x, Q^2)$
- Clear effect of deuteron D-wave, largest in the region dominated by the tensor part of the  $NN$ -interaction
- D-wave drops out at the on-shell point

# Use Bonus data: $F_{2n}/F_{2p}$

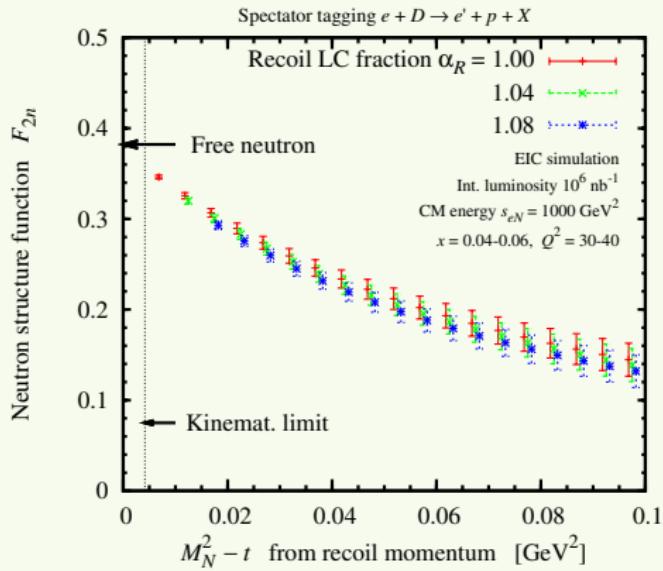


WC, M. Sargsian, PRC93 '16

- Robust results wrt deuteron wave function, fsi parameters, normalization of the data used in the extraction.
- Good agreement with Christy, Bosted parametrization at lower  $x$  values
- **Striking rise** of the ratio at high  $x$ , but **sub-DIS  $Q^2$**
- Relevant for the dynamical generation of high-momentum quarks [imbalanced Fermi systems]

# Tagging: free neutron structure

## Precise measurements of $F_{2n}$

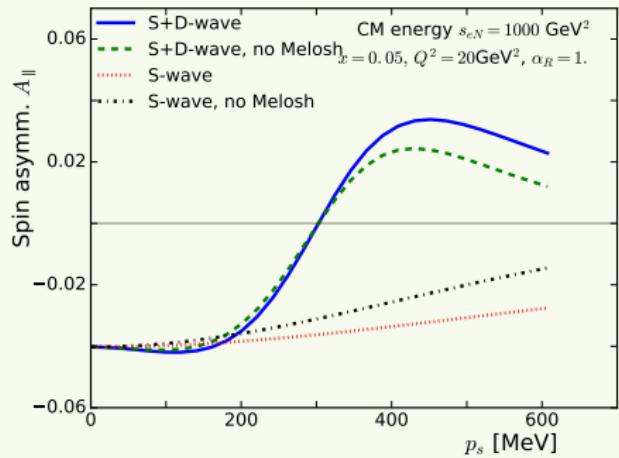


JLab LDRD arXiv:1407.3236, arXiv:1409.5768

- $F_{2n}$  extracted with percent-level accuracy at  $x < 0.1$
- Uncertainty mainly systematic ([JLab LDRD project: detailed estimates](#))
- In combination with proton data non-singlet  $F_{2p} - F_{2n}$ , sea quark flavor asymmetry  $\bar{d} - \bar{u}$

# Polarized structure function $F_{LS_L}$

## ■ Spin asymmetry



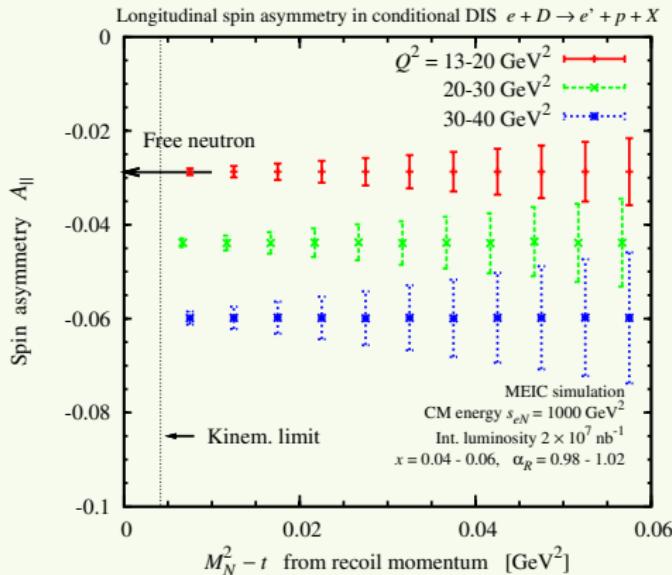
$$A_{\parallel} = \frac{\sigma(++) - \sigma(-+) - \sigma(+-) + -\sigma(--)}{\sigma(++) + \sigma(-+) + -\sigma(+-) + -\sigma(--)} [\phi_h^{\text{avg}}]$$
$$= \frac{F_{LS_L}}{F_T + \epsilon F_L} \propto \frac{g_{1n}}{F_{1n}}$$

- Again clear contribution from D-wave at finite recoil momenta
- Relativistic nuclear effects through Melosh rotations, grow with recoil momenta
- Both effects drop out near the on-shell extrapolation point

# Tagging: polarized neutron structure

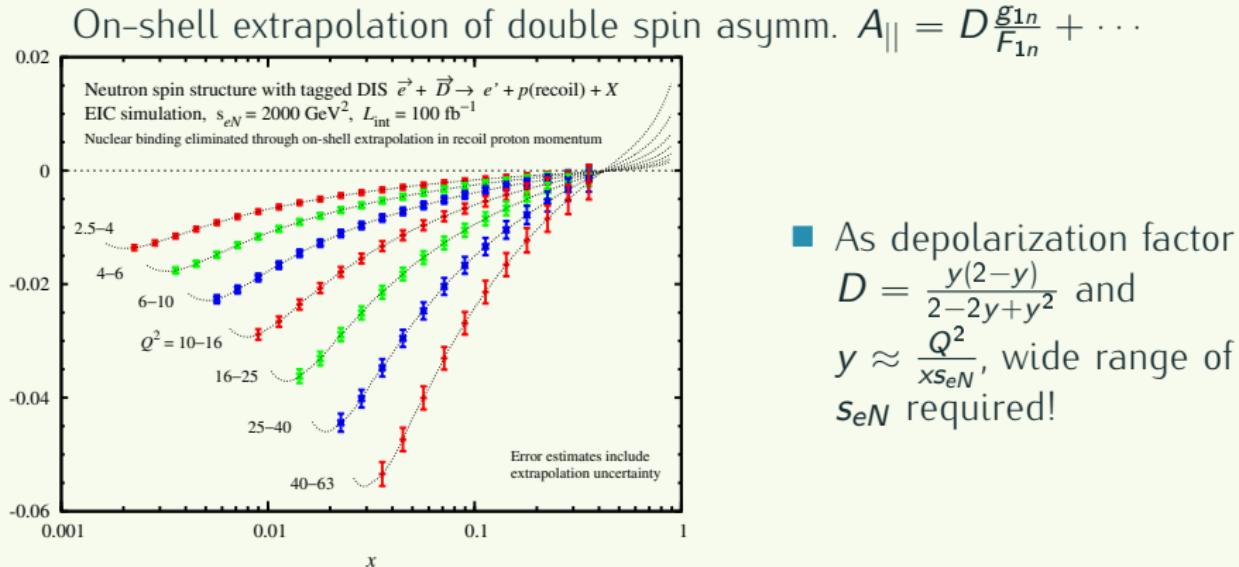
On-shell extrapolation of double spin asymm.

$$A_{||} = \frac{\sigma(++) - \sigma(-+) - \sigma(+-) + -\sigma(--)}{\sigma(++) + \sigma(-+) + -\sigma(+-) + -\sigma(--)} [\phi_h \text{avg}] = \frac{F_{LS_L}}{F_T + \epsilon F_L} = D \frac{g_{1n}}{F_{1n}} + \dots$$



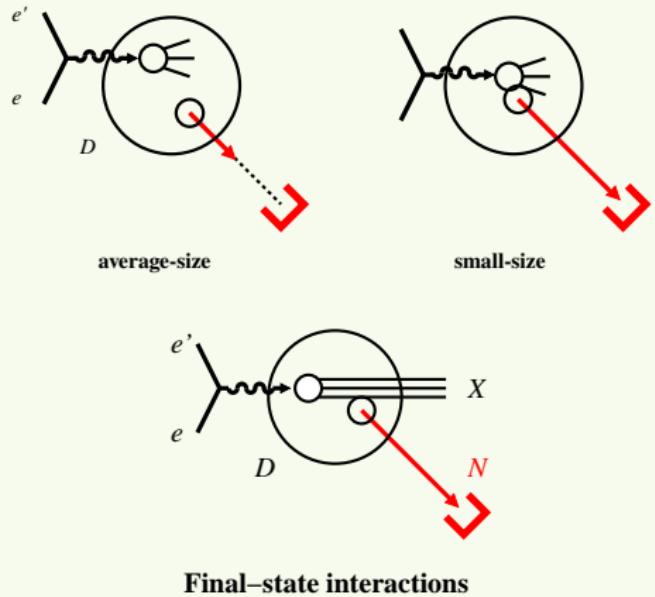
- Systematic uncertainties cancel in ratio (momentum smearing, resolution effects)
- Statistics requirements
  - ▶ Physical asymmetries  $\sim 0.05 - 0.1$
  - ▶ Effective polarization  $P_e P_D \sim 0.5$
  - ▶ Luminosity required  $\sim 10^{34} \text{ cm}^{-2} \text{s}^{-1}$

# Tagging: polarized neutron structure II



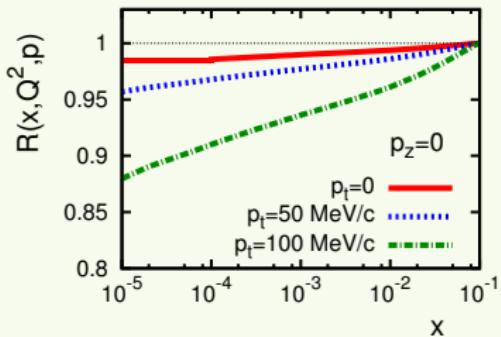
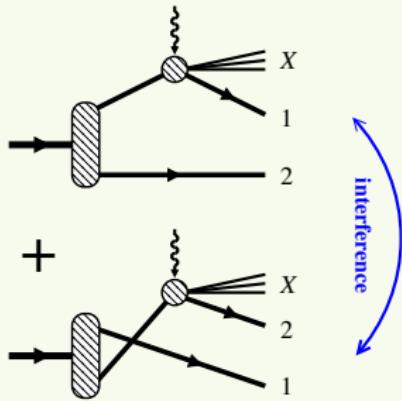
- Precise measurement of neutron spin structure
  - ▶ separate leading- /higher-twist
  - ▶ non-singlet/singlet QCD evolution
  - ▶ pdf flavor separation  $\Delta u, \Delta d, \Delta G$  through singlet evolution
  - ▶ non-singlet  $g_{1p} - g_{1n}$  and Bjorken sum rule

# Tagging: EMC effect



- Medium modification of nucleon structure embedded in nucleus (EMC effect)
  - ▶ dynamical origin?
  - ▶ caused by which momenta/distances in nuclear WF
  - ▶ spin-isospin dependence?
- tagged EMC effect
  - ▶ recoil momentum as extra handle on medium modification (off-shellness, size of nuclear configuration) away from the on-shell pole
  - ▶ EIC:  $Q^2$  evolution, gluons, spin dependence!
- Interplay with final-state interactions!
  - ▶ use  $\tilde{x} = 0.2$  to constrain FSI
  - ▶ constrain medium modification at higher  $\tilde{x}$

# Tagging: Coherence and shadowing at small $x$



- Shadowing in inclusive DIS  $x \ll 10^{-1}$ 
  - ▶ Diffractive DIS on single nucleon (leading twist, HERA)
  - ▶ Interference of DIS on nucleon 1 and 2
  - ▶ Calculable in terms of nucleon diffractive structure functions [Gribov 70s, Frankfurt, Guzey, Strikman '02+]
- Shadowing in tagged DIS
  - ▶ Explore shadowing through recoil momentum dependence [Guzey, Strikman, Weiss; in progress]
  - ▶ Reveal nuclear momentum components building up coherent fields at small  $x$
  - ▶ Study coherence in  $A = 2$ , complimentary to  $A \gg 1$
- Coherent scattering  $e + D \rightarrow e + M + D$   
Exclusive meson production, DVCS, nuclear GPDs

# Tagging: developments and extensions

- Final-state interactions in tagged  $e + D$ 
  - ▶ distorts recoil momentum dependence away from the on-shell pole  $t \neq m_N^2$
  - ▶ broad momentum distribution, interactions of spectator with slow debris  
[Cosyn, Sargsian, Strikman, Weiss; in progress. Ciofi, Kopeliovich 02]
  - ▶ maximized/minimized by choice of kinematics. Constrain FSI models.
  - ▶ azimuthal and spin observables non-zero through FSI
- Tagging with complex nuclei  $A > 2$ 
  - ▶ isospin dependence, universality of bound nucleon structure
  - ▶  $A - 1$  ground state recoil
- Resolved final states: SIDIS on neutron, hard exclusive channels

# R&D project at JLAB

- Develop simulation tools (physics models, event generators, analysis tools) for DIS on light ions with spectator tagging at MEIC and study physics impact.

- ran FY14-15

D. Higinbotham, W. Melnitchouk, P. Nadel-Turonski, K. Park, C. Weiss (JLab), Ch. Hyde (ODU), M. Sargsian (FIU), V. Guzey (PNPI), with collaborators W. Cosyn (Ghent), S. Kuhn (ODU), M. Strikman (PSU), Zh. Zhao (JLab)

- Tools, documentation, results publicly available. Open for collaboration!

- More info:

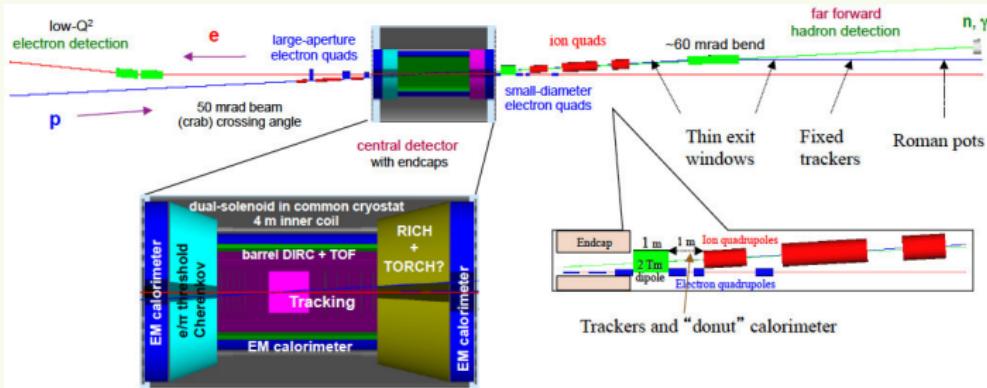
<https://www.jlab.org/theory/tag/>

arXiv:1407.3236, arXiv:1409.5768v1, arXiv:1601.066665,  
arXiv:1609.01970

# Conclusions

- Wealth of possibilities with spectator tagging DIS
  - ▶ control over the nuclear configuration
  - ▶ pole extrapolation allows for on-shell nucleon extraction in a **model independent** way
- Cross section for polarized SIDIS with spin 1 target, new opportunities in the tensor polarized SFs
- Clear effects from nuclear structure and relativistic spin away from the pole
- Neutron (spin) structure extraction possible in a wide kinematic range at EIC
- Lots left to explore, this is just the beginning...

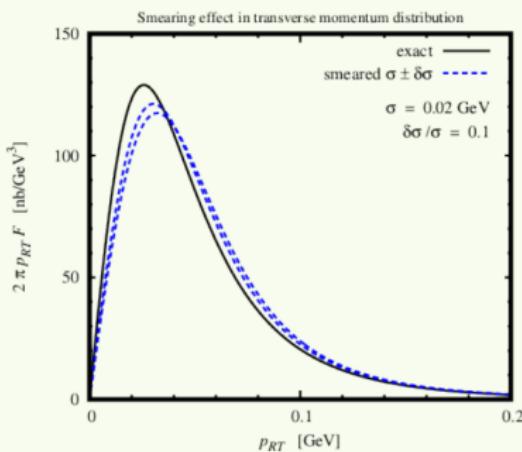
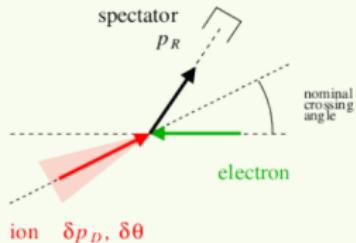
# JLEIC full-acceptance detector



P. Nadel-Turonski et al.

- Forward detector integrated in interaction region & beam optics
- Good acceptance for elastic recoil  
Rigidity same as beam. Large dispersion generated *after* IP  
Longitudinal momentum up to 99.5% of beam, angles down to 2 mrad (10  $\sigma$ )
- Good acceptance for spectators and ion fragments  
Rigidity different from beam. Large magnet apertures, small gradients
- Good momentum and angular resolution  
Longitudinal  $dp/p \sim 4 \times 10^{-4}$ , angular  $\delta\theta \sim 0.2$  mrad  
 $p_{TR} \sim 15 \text{ MeV}/c$  resolution for tagged 50 GeV/A deuterium beam

# JLEIC: Momentum spread in beam



- Intrinsic beam spread in ion beam "smears" recoil momentum
  - ▶ transverse momentum spread of  $\sigma \approx 20$  MeV ( $\delta\sigma/\sigma \sim 10\%$ )
  - ▶  $p_R(\text{measured}) \neq p_R(\text{vertex})$
  - ▶ Systematic correlated uncertainty,  $x, Q^2$  independent
- Dominant syst. uncertainty at JLEIC, detector resolution much higher than beam momentum spread (diff for eRHIC)
- On-shell extrapolation feasible!!